Forests, carbon, fire and water security: development of capability for landscape risk analysis:
The *Dynamic Landscape Simulator (DLS)* v.0.1

AICAS Scoping Study report

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EXECUTIVE SUMMARY

Integrative landscape management sits at the confluence of several major environmental issues and associated policy decisions concerning carbon sequestration, water security for growing cities, and fire management for fuel reduction to reduce wildfire risk to life and property. Integrative management requires simultaneously assessing the impacts of management decisions on multiple ecosystem properties, such as carbon sequestration, wildfire regimes, catchment water yields, and biodiversity habitat. Because many of these ecosystem properties interact with and respond nonlinearly to different management regimes, numerical analysis frameworks are required to assist with the assessment of the potential impacts and trade-offs associated with different management options. Such integrative tools for Australian native forest management currently do not exist.

To address this gap, this study describes a prototype landscape simulation tool that combines dynamic (time-varying) and spatially explicit submodels of vegetation carbon growth and decay, catchment hydrology, and fire spread and fuel combustion. The resulting prototype software (the Dynamic Landscape Simulator (DLS) v0.01) links these submodels to provide a full-system approach to investigating landscape dynamics and responses. Model analysis is based on the Monte-Carlo simulation of different management scenarios; i.e. each scenario is run a large number of times, and the statistical properties of the ensemble of runs are reported. This is necessary because many of the underlying processes are stochastic (e.g. the dynamics of wildfire), and therefore a large number of random ‘realisations’ are required to build up a representative picture of the likely impacts of different management options, and the uncertainty associated with those options. The underlying sub-models were kept as simple as possible, recognising that it is always easier to incrementally add complexity onto an initially simple framework.

Spatially-explicit and temporally dynamic ecosystem modelling generates large amounts of numeric output, especially when model runs are replicated numerous times. To simplify and facilitate the communication of this complex set of outputs a new graphical device is proposed: the Landscape Management Assessment Chart (LMAC). This graphical summary is designed to communicate, at a glance, the implications and trade-offs associated with different management options across a range of ecosystem properties.

Illustration of the software and of the use of the LMAC is provided through two hypothetical management scenarios applied to a test catchment. In the first, the application of a prescribed burn buffer around key infrastructure elements within a landscape is compared against a regime of no prescribed burning, and the efficacy of the prescribed burns on mitigating wildfire risk is assessed, together with co-impacts on a range of other ecosystem attributes. In the second, a scenario is developed to simulate the impacts on catchment flows resulting from the establishment of plantation trees on previously cleared land. The potential to construct more realistic scenarios combining e.g. fire management, timber harvesting and tree planting is discussed.

The report concludes with a review of the work required to extend the current ‘proof of concept’ tool to one suitable for undertaking a fully-fledged case study. The key short-term priorities are revisions to the catchment hydrology and fire algorithms, improved representation
of nutrient constraints on carbon gain and vegetation water use, and more rigorous calibration and validation against field datasets. In the longer term the key priorities include extending the scope of the framework to allow investigation of the impacts of global climate change on vegetation dynamics and disturbance regimes, and extensions to include the socio-economic aspects of landscape decision making.
1. INTRODUCTION

Native forests sequester and store significant amounts of carbon (Australian forest biomass CO$_2$-e stocks are approximately 50x-100x Australia’s annual emissions; MPIGA 2008), yet during bushfire events this same biomass when alight threatens life and property and releases enormous quantities of CO$_2$ and other greenhouse gasses. For policy this represents a paradox between protecting and enhancing the role of forests as both carbon sinks and for biodiversity value, and managing and reducing fuel loads to reduce fire hazard. Similarly, forested catchments provide most of the fresh drinking water in Australia, yet young fast growing forests regenerating after fires can significantly reduce catchment flows.

Fire and forests are likely, therefore, to sit at the confluence of major issues and policy decisions concerning carbon sequestration, water security for growing cities, and fuel reduction to reduce risk to life and property in peri-urban areas. Predictions of increased bushfire risk under climate change will increase these challenges (Hennessy et al. 2005). Recent reviews (Garnaut 2008; CSIRO 2009) and the draft ETS legislation (DCC 2009) have foreshadowed the role of forest management in carbon sequestration. Because carbon is only one of many services provided by native forests, integrative analysis is required to answer questions regarding the trade-offs among multiple ecosystem functions and management, such as:

- What effect on forest carbon stocks and biodiversity values would result from fuel reduction programs that effectively reduced fire risks in peri-urban areas?
- How will fire regimes under climate change scenarios impact on native forest carbon and water security?
- If we choose to manage urban catchments for water security by reducing the risk of large, high intensity fires what are the implications for carbon stocks and biodiversity habitat?

These key policy questions surrounding native forest management and associated environmental costs and benefits will require decision support frameworks of various forms to help answer. In anticipation of this, this scoping project seeks to develop a prototype modelling framework to facilitate decision support for native forest management, with a focus on quantifying multiple environmental costs and benefits; such integrative tools for Australian native forest management currently do not exist.

Linking the dynamics of native forest carbon and water at landscape/catchment-scales, and quantifying the interactions of these cycles with wildfire, fire management and biodiversity is a formidable research challenge, particularly given the background of a changing climate. Individually there exist many models for describing forest carbon growth, fire dynamics and catchment hydrology, at a range of levels of complexity and process description. The challenge for developing integrated assessment tools is to first specify the conceptual framework for how the various components interact, and second, to select the most appropriate sub models and algorithms for inclusion. A difficulty for any analysis that seeks to integrate across multiple processes and disciplines is finding the right balance between model complexity and process
description, data availability, and the appropriate level of simplification to allow tractable but meaningful analysis (Argent & Grayson 2003).

This scoping study outlines a prototype software analysis framework and visualization tool as a step towards this goal. The study seeks to clarify a conceptual model for how the various subcomponents interact (carbon, fire, water), and to translate that conceptual model into a demonstration software package. This demonstration software includes placeholder algorithms to illustrate indicative model outputs and analyses, provides a proof-of-concept of the overall approach, and provides the architecture on which future full development capacity can be built. There are three advantages of this staged approach:

- Defining a robust and mutually-agreed conceptual model of the full system provides a solid basis for ongoing scientific discussion and revision.
- Translating the conceptual model of the system into a formal mathematical framework, through making explicit the links and dependencies, assists in identifying key research gaps and data requirements/limitations.
- Translating the conceptual model provides a tangible visualisation product and demonstration tool of analysis capability, and provides the basis for more extensive development and analysis.

2. A CONCEPTUAL FRAMEWORK FOR MODELLING LANDSCAPE PROCESSES

The primary goal of this project is to provide a capacity to simultaneously assess the trade-offs and implications surrounding different landscape-scale management decisions on key ecosystem services; catchment water yield, carbon sequestration, and biodiversity habitat. The range of management activities includes but is not limited to:

- Application of prescribed fire for (a) asset protection and/or (b) ameliorating wildfire risk
- Timber harvesting
- Land clearing, and
- Revegetation of previously cleared land.

A spatially-explicit, landscape-scale analysis is advocated for this task. This is necessary for a number of reasons. First, management decisions are undertaken within a specific spatial context, e.g. decisions on what parts of the landscape are to be harvested, forested, or prescribe-burnt must take into account the spatial distributions of key landscape elements, such as the locations and relative positions of waterways, roads, electrical transmission lines, built-up areas and vegetation distribution etc. Second, the management activities are themselves spatially defined, e.g. there is often a choice of alternative land units to be harvested, prescribed burnt, or re-planted. Third, fire spread, catchment hydrology and the spatial distribution of plant growth
and decomposition processes are all spatial phenomenon, and the rates of matter and energy transfer associated with those processes are influenced by both their locations within the landscape, and their spatial relationship to other landscape elements (Forman & Godron 1986). Finally, at landscape-scales topographic variability and its influence on the balance of energy and water budgets, and their interactions with the biota, is well appreciated (Mackey et al. 2002). These topographic controls on the primary drivers of plant growth and decomposition therefore need to be included, either explicitly or implicitly, in any modelling assessment of landscape processes involving vegetation management.

The next two sections describe the conceptual basis for the software design. The remainder of the report describes the implementation of this conceptual model into a demonstration software tool.

2.1 A simple conceptual model linking ecosystem carbon, water and disturbance

Three interacting sub-models (carbon sub-model, water sub-model, disturbance sub-model) describe the key underlying processes. Each sub-model is based on a set of dynamic (differential) equations. The conceptual model is kept deliberately simple, to highlight the fundamental linkages among the processes.

For practical implementation of the conceptual model the flux terms that occupy the right hand sides of these fundamental equations need to be specified. They are typically complex functions that require a range of inputs such as climate drivers and environmental variables (e.g. topography, soil characteristics), in addition to sets of user-defined parameters which relate those inputs and define the nature of the dynamics (e.g. specifying how spatial variation is incorporated, linear vs. non-linear functional relationships, etc.). The actual implementation of this conceptual model within the software, i.e. the equations defining the primary flux terms, is described in Section 3.

2.1.1 Carbon submodel

At any given point in the landscape, the growth rate of vegetation, the production of litter and its decay, and the incorporation and loss of organic carbon to and from the soil can be represented by the following:

\[
\frac{dC_{\text{Living}}}{dt} = NPP - M_{\text{Living}} \tag{1}
\]

\[
\frac{dC_{\text{Litter}}}{dt} = M_{\text{Living}} - D_{\text{Litter}} - H_{\text{Litter}} \tag{2}
\]

\[
\frac{dC_{\text{Soil}}}{dt} = H_{\text{Litter}} - D_{\text{Soil}} \tag{3}
\]
Where $C_{Living}$, $C_{Litter}$, and $C_{Soil}$ represent the pools of carbon in living vegetation, dead vegetation and the soil respectively (the five primary flux terms $NPP$, $M_{Living}$, $D_{Litter}$, $H_{Litter}$ and $D_{Soil}$ are described in Table 1). For any practical application, the three major ecosystem C pools require further sub-division to reflect both functional variability within the ecosystem (e.g. different soil organic carbon (SOC) pools with varying C residency times) and structural variability (e.g. stems vs. branches and leaves; overstorey vegetation vs. understorey vegetation and fuels). As an example, the implementation of Equations 1-3 in the prototype model described in Section 3 includes four living C pools, four litter C pools, and five soil C pools.

The five primary ecosystem fluxes all vary temporally with climatic and environmental conditions, and also spatially across landscapes, particularly in response to topographic variability. When implementing the above equations the structure and functioning of different vegetation types (e.g. grassland vs. native forest vs. plantation) can be specified through vegetation-specific choices of the equations specifying the fluxes and their associated parameters. The units for the C fluxes are often given as either gC/m$^2$/time, or tC/ha/time, where the choice of timescale is defined by the time interval over which equations 1-3 are numerically integrated (Roxburgh et al. 2005). Monthly intervals are convenient for describing vegetation growth and decay over decadal-to-century timeframes. However, many models utilise shorter intervals depending on the ecosystem processes that are of primary interest, e.g. daily and sub-daily integration intervals are also common.

### Table 1: Explanation of carbon model flux terms.

<table>
<thead>
<tr>
<th>Flux term</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NPP$</td>
<td>Net Primary Production. The net rate of photosynthesis (total plant photosynthesis less plant respiratory requirements)</td>
</tr>
<tr>
<td>$M_{Living}$</td>
<td>The rate at which living plant biomass is added to above- and below-ground litter pools. Includes leaf fall, branch drop, and mortality.</td>
</tr>
<tr>
<td>$D_{Litter}$, $D_{Soil}$</td>
<td>The rate at which soil and litter decomposes, releasing CO$_2$ back to the atmosphere</td>
</tr>
<tr>
<td>$H_{Litter}$</td>
<td>The rate at which litter is incorporated into the soil organic carbon pool</td>
</tr>
</tbody>
</table>

#### 2.1.2 Water submodel

At a given point in the landscape, the mass of water held in the soil can be represented by the following:

$$\frac{dW_{Soil}}{dt} = (P + I) - E - T - R - D$$

Where $W_{Soil}$ represents the soil water content. The five water fluxes (Precipitation, $P$; Irrigation, $I$; Evaporation, $E$; Transpiration, $T$; Surface Runoff, $R$, and Drainage, $D$) also vary spatially across a landscape, e.g. through altitudinal gradients in precipitation, changes in soil properties, and topographic influences affecting runoff and drainage. Analogous to the carbon model, the soil water content is often separated into compartments, usually representing different depth
layers, reflecting differences in such important contributors to the water balance as rooting depth and root architecture, and changes in soil horizon properties.

In the context of interactions among the sub-models, the key water flux is the transpiration loss, which is a direct function of vegetation growth \((NPP)\), and is variable with respect to stand age, fertility etc. Linking the carbon and water sub-models via transpiration reflects the mutual feedback between these two fluxes; vegetation NPP is a function of (and is often limited by) the available soil water content. Reciprocally, as vegetation grows, water is drawn from the soil store and lost via transpiration through the stomatal openings. Catchment water yield (catchment runoff) is the sum of the surface runoff and drainage terms, and can be compared against streamflow data where available. This explicit link between vegetation growth and catchment water balance allows impacts of changes to vegetation structure and function on streamflow to be assessed. Examples include fluctuations in water supply stemming from the fire-renewal cycle (Wood et al. 2008) and the implications of changing vegetation cover via e.g. either tree planting or vegetation clearing (Marcar et al. 2010).

As with the carbon sub-model, the six flux terms on the right hand side of the Equation 4 are, in general, functions of both spatially and temporally varying environmental conditions.

2.1.3 Disturbance submodel

**Specifying the effects of disturbance on carbon and water**

There are two aspects to the disturbance model. The first is specifying the direct effect of a disturbance event on the balances of carbon and water. For carbon (Equations 1-3), disturbance impacts are assumed to be instantaneous. I.e., if a location is e.g. burnt, then the carbon stocks are modified according to:

\[
C'_{Living} = (1 - f_{Living}) \times C_{Living}
\]

\[
C'_{Litter} = (1 - f_{Litter}) \times C_{Litter}
\]

\[
C'_{Soil} = (1 - f_{Soil}) \times C_{Soil}
\]

Where \(C_{Living}, C_{Litter}\) and \(C_{Soil}\) are the carbon stocks immediately prior to disturbance, \(C'_{Living}, C'_{Litter}\) and \(C'_{Soil}\) are the carbon stocks immediately after disturbance, and \(f_{Living}, f_{Litter}\) and \(f_{Soil}\) represents the fraction of each carbon pool that is emitted or otherwise lost due to the disturbance event.

The flow-on effects of the disturbance event are included through the connections between the carbon pools directly affected, and other aspects of the carbon and water cycle. For example a fire or other disturbance that kills or severely defoliates living vegetation leads to changes in ecosystem NPP, which through the linkage between plant growth and plant water use (transpiration) leads to a perturbation of the overall water balance, i.e. changes to soil water storage and catchment runoff.
The loss fractions \( (f) \) can be specified in many ways, and in general will be both spatially and temporally variable. For example in the implementation of Equations 5-7 described in Section 3, the fraction of the carbon pool affected by wild fire is a function of the fire behaviour, which is itself a function of prevailing weather conditions, current fuel loads and topographic position.

Most management impacts can also be treated as a disturbance. For example the effects of prescribed burning, timber harvesting and land clearing can be also be represented via Equations 5-6. The major difference between what constitutes ‘management’ and ‘disturbance’ lie in the rules that specify the particular disturbance or management regime. For example the impacts of both prescribed fire and wildfire can be represented by Equations 5-7, though typically with different loss fractions \( (f) \). However, wildfire is generally unpredictable and is primarily a function of prevailing weather conditions and landscape dryness, and hence evolves as a dynamic output of a model run. In contrast, a prescribed burning regime is specified \textit{a priori} as part of a suite of proposed management actions.

\textit{Specifying the disturbance regime}

The second aspect of the disturbance submodel requires specifying the algorithms/data inputs that define the disturbance regime. The disturbance regime defines the suite of attributes specific to the spatial and temporal extents of disturbance, and include disturbance frequency, intensity, extent, duration and timing (Shea \textit{et al.} 2004). In the case of wild fire this might involve the rules that specify the ignition, spread, and extinguishment of fire across a landscape (Keane \textit{et al.} 2003). For timber harvesting or land clearing it might involve assessing land tenure status and specifying appropriate harvesting rates, and the timing of any management such as tree thinning, prescribed burning etc. The nature of the rules and associated algorithms defining the disturbance regime is therefore specific to the problem at hand, and cannot be expressed as generalised equations.
2.2 Overall structure of the conceptual model

The linkages between the carbon, water and disturbance submodels, as described by Equations 1-7, are represented in diagrammatic form in Figure 1. Note for simplicity there are a number of potential fluxes that are not represented in equations 1-7 (and therefore not shown in Figure 1), such as fire-induced formation of soil char and the creation of dead stags and ground litter. These are important components of the vegetation response to disturbance, and need to be included in a full implementation of the conceptual model.

Figure 2. Conceptual model linking environmental disturbance with the carbon and water cycles. The diagram represents equations 1-7, and the state variables (boxes) and fluxes (arrows) are labelled to match the terms in those equations. Blue represents water, green is carbon, and red is disturbance. The dashed lines for the disturbance flux and the associated red areas within each carbon pool indicate this flux is instantaneous/event-driven, whereas all other fluxes are continuous in time.
3. COMMUNICATION OF MODEL RESULTS: *Landscape Management Assessment Charts (LMACs)*

Before describing the implementation of the conceptual model it is worth taking a step back and asking what the key outputs of such an analysis tool should be, and how those outputs could be best communicated.

Because the intent is to assess changes in management regimes, rather than specific events, a Monte-Carlo approach is adopted. This involves defining a management scenario, and then running that scenario many times in order to generate a ‘family’ of possible outcomes. This is necessary because there are stochastic elements to many of the calculations, e.g. the occurrence of wildfire; therefore simulating many ‘possible’ outcomes for a given scenario provides a robust estimation of the range of possible impacts.

The number and format of possible model outputs generated from the replicated spatio-temporal modelling of carbon, water, disturbance and management dynamics is potentially very large. In order to simplify and synthesise the resulting information, and to make it digestible to a non-technical audience, we introduce the concept of the Landscape Management Assessment Chart (LMAC). This is best illustrated with an example.

Figure 2a shows a hypothetical landscape, with some key infrastructure (black squares) located within a cleared area (yellow) and surrounded by bushland (green). In order to better protect that infrastructure from wildfire, a regime of prescribed hazard reduction burns is proposed (Figure 2b).

The steps for assessing the effectiveness of the proposed prescribed burning regime for protecting the infrastructure, together with assessments of the co-impacts on catchment water
yield, carbon storage, biodiversity habitat and ameliorating the risk of wildfire, requires simulating, over time, changes in carbon storage and catchment flows for the current/historical management regime (assumed to be no fire management), and then comparing that against the proposed alternatives of, for example, applying prescribed fire to the area shown in Figure 2b at frequencies of 2, 3, 5, 10 and 20 years. A possible resulting LMAC for this hypothetical example, summarising perhaps hundreds of individual model runs, is shown in Figure 3.

The figure shows the range of management options on the x-axis, and key ecosystem responses on the y-axes. The green marker represents the assumed current management activity of no prescribed burn, whereby:

a. The probability of at least one of the infrastructure locations (the black squares in Figure 2) experiencing a wildfire front over a 100 year simulation period is 0.75

b. The proportion of the landscape burnt by wildfire, over the period of the simulation, is 0.5.

c. The current ecosystem carbon storage is 250tC/ha.

d. The mean annual catchment runoff is 50ML/yr, and

e. a relative index of age-class heterogeneity (a proxy for habitat diversity) is 0.5

The grey arrow shows the predicted impact of adopting a prescribed burning frequency of every 5 years. Adopting this ‘5-yr’ burning scenario and comparing it to the current management suggests:

a. The probability of a fire front passing over the infrastructure is reduced from 0.75 to 0.5.

b. The proportion of the landscape burnt by wildfire decreases from 0.5 to 0.4.

c. The current ecosystem carbon storage decreases from 250tC/ha to 200tC/ha

d. The mean annual catchment runoff increases from 50 to 60 ML/Month, and

e. The index of habitat diversity remains the same at 0.5.

Importantly, the LMAC framework allows a range of alternative management scenarios to be assessed simultaneously against a number of measures of ecosystem function. Although the hypothetical example involved only prescribed burning within a single area, more realistic alternative management scenarios might combine a prescribed burning regime involving different frequencies implemented asynchronously across a mosaic of patches, and could also simultaneously incorporate other interventions such as a range of fire suppression responses, timber harvesting, plantation establishment or clearing.

The hypothetical example also highlights the potential importance of identify nonlinearities in the ecosystem responses. For example, responses that are relatively constant across a range of management options, but then reach a threshold beyond which the change is more rapid (e.g. the proportion of the landscape burnt by wildfire); and also ‘humped’ or other non-monotonic responses, such as that for the biodiversity index, which is expected to follow such a curve based on the Intermediate Disturbance Hypothesis (Shea et al 2004). The presence of such nonlinearities require care when assessing impacts and trade-offs across disparate ecosystem measures.
Figure 4. Hypothetical Landscape Management Assessment Chart (LMAC) to summarise model outputs. The x-axis lists the range of management options under consideration (including current/historical management in green), and the y-axis quantifies the respective responses of a range of ecosystem attributes. The grey arrows show the expected changes associated with a change in management from no-burn, to a prescribed burn (of the area shown in Figure 2b) every 5yrs.
4. IMPLEMENTATION OF THE CONCEPTUAL FRAMEWORK: THE Dynamic Landscape Simulator (DLS) v0.1

4.1 Model Overview

The modelling framework is built upon existing algorithms and technologies. Previous experience gained in the development of software for spatial environmental analysis (Roxburgh & Davies 2006), risk assessment (Hill, Roxburgh et al. 2005, 2006) and carbon modelling (Roxburgh et al. 2005, 2006; Dean, Roxburgh & Mackey (2003, 2004) was used to inform the initial choice of software platform, software architecture, and underlying algorithms.

Because landscape analysis is an inherently spatial problem, GIS software and analysis has a significant role to play in the analysis and generation of the required data. However, native GIS software performs poorly for numerically intensive (temporally) dynamic modelling (Argent & Grayson 2003; Roxburgh & Davies 2006), hence the prototype system is coded in Borland Delphi© for the windows environment. This choice of platform is based on the availability of existing algorithms for handling spatial data, algorithms for vegetation and fuel dynamics, for numerical integration and code parallelisation, and for data visualisation. Delphi applications are also ‘stand-alone’, and can be distributed and run without any requirement for other software packages. Other platforms and alternative options for distribution are discussed in the last section.

For the prototype software (DLS v.0.1), only placeholder functions & models are used as caricatures of the underlying dynamics. A single catchment is used to demonstrate potential capability, selected based on landscape suitability and data availability.

It is important to note that the proposed modelling framework is not intended to simulate the implications of specific events e.g. the impacts of a particular fire occurrence. Rather, the software is designed such that Monte-Carlo and ensemble runs are used to generate probability distributions of the consequences of different management scenarios. The intended use is therefore for making robust general predictions and recommendations regarding changes to management regimes (Coreau et al. 2009), rather than as a predictive tool for assessing specific events.

4.2 Implementation details

The conceptual model as described by Equations 1-7 provides the overarching framework within which a wide range of landscape models could be constructed. In particular, embedded within the state variables (the carbon and water stocks) and their associated fluxes is an implicit (though undefined) spatial and temporal extent; i.e. the equations could describe the dynamics within a small patch, or they could be continental in scale.

For a practical implementation of Equations 1-7 decisions need to be made on the spatial and temporal scale of application, and of the most appropriate subdivision of the state variables into sub-pools to better reflect ecosystem heterogeneity (e.g. splitting \( C_{living} \) into photosynthetic
tissue, above-ground stems and branches, below-ground roots, etc). Our implementation of the conceptual model is called the DLS (Dynamic Landscape Simulator), and is based on the following premises.

4.2.1 Spatial scale

The stated aim of this work is to provide a capacity to assess the implications of different management options on landscape structure and function, and on the environmental trade-offs associated with those different options. As argued in Section 2, many management decisions are made within a spatial context, and therefore an implementation of Equations 1-7 that explicitly recognise both the spatial extent and the relative locations within landscapes is required. It was also noted in the Introduction that topographic variation plays an important role in determining vegetation growth and decay processes, and in constraining the management options that are available.

Because one of the primary analysis goals is to address the impacts on ecosystem water yield, the logical unit of analysis is the catchment, thus facilitating the comparison of model outputs to stream gauge measurements. Note that the ‘catchment’ scale still affords a wide range of choice for total analysis extent, as hydrological catchments (and sub-catchments) can range from a few hectares to many hundreds of square kilometres. Regarding the representation of sub-catchment heterogeneity, the DLS adopts a grid-based approach, with a unit gridcell size of 25m x 25m. This scale reflects the highest resolution spatial data that is readily available for many catchments; though data can be automatically aggregated within the software for analysis at coarser scales, i.e. greater than 25m x 25m (see Appendix B). The DLS application of the conceptual model Equations 1-7 therefore involves simulating the dynamic carbon, water and disturbance submodels within each gridcell, across the whole study catchment.

The Goobragandra catchment within NSW was selected to provide a context for the initial software development. This catchment comprises a mixture of cleared land, Pinus radiata plantation and native forest (Figure 4). It measures approximately 38km N-S and 27km E-W, and is located in mountainous terrain near the town of Tumut, NSW.

Figure 5. The Goobragandra catchment within NSW was selected to develop and test the initial version of the model. (a) Digital elevation model. (b) current land use.
4.2.2 Temporal scale

Many of the processes that influence carbon, water and disturbance dynamics are functions of the climate. Where weather station records are available within study catchments then they can be used; however in many cases such data are not available, or have missing records. In the absence of suitable station records, climatic data can be obtained from the SILO product (Jeffrey et al. 2001; http://www.longpaddock.qld.gov.au/silo/), where station records are spatially interpolated to generate predictions of climate variables for any location within Australia. These are available from 1890 to the present, at a daily resolution.

Because ecological processes operate at a range of temporal scales, ecosystem models often reflect this through having flexibility in their temporal scale of analysis. For the DLS plant growth (NPP), litter decay and soil processes all operate at a monthly scale, and in the current implementation the water balance is also calculated monthly. Monthly climatic data are summarised at load time from the input daily records for each climate variable (Figure 5). In contrast, the wildfire spread algorithm has been configured to run at sub-monthly timesteps, with a default timestep of hours (see Section 4.2.4 below).

Figure 6. Mean monthly rainfall and daily maximum temperature for the Goobragandra catchment.

4.2.3 Input data requirements

Spatial data

Spatial data are input into DLS as standard ArcGIS float export format, georeferenced to the same equal-area projection. For continuous data (e.g. digital elevation model, topographically corrected solar radiation) the required files are the data (*.flt) and associated header (*.hdr). Some of the spatial input data is categorical, with a map index number linked to a look-up attribute table. This provides the capacity for a single map layer to contain a range of input data (for example a soil map, with a range of attribute values for each location, e.g. soil class, soil depth, water holding capacity, etc). Categorical data requires a standard ArcGIS database attribute table to be associated with the map (*.dbf).

The list of spatial data required to run DLS is given in Table 2.
Table 2: Spatial input data required by DLS.

<table>
<thead>
<tr>
<th>Spatial data</th>
<th>Continuous or categorical?</th>
<th>Description</th>
<th>How used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment mask</td>
<td>Categorical</td>
<td>Defines the catchment extent (0,1)</td>
<td>Used to define the catchment boundary.</td>
</tr>
<tr>
<td>Digital Elevation Model (DEM)</td>
<td>Continuous</td>
<td>Elevation (in m) above sea level.</td>
<td>Used in the fire spread algorithm to determine whether the fire is currently burning uphill or downhill.</td>
</tr>
<tr>
<td>Monthly (1..12) topographically corrected solar radiation.</td>
<td>Continuous</td>
<td>Monthly solar radiation calculated in ArcGIS from the DEM according to (Dyer 2009). MJ/m²/day</td>
<td>Used in the light use efficiency equation to determine light-limited NPP.</td>
</tr>
<tr>
<td>Climate zones</td>
<td>Categorical</td>
<td>A classification of the catchment into zones for the purposes of generating spatio-temporal variability in climate. An index 1..n, where n is the number of zones.</td>
<td>For the test catchment four zones were classified based on altitude. A SILO climate data file was extracted for each zone.</td>
</tr>
<tr>
<td>Land cover</td>
<td>Categorical</td>
<td>A classification of the catchment based on land cover. A unique land use/land cover change history is associated with each polygon, thus dynamic changes in vegetation cover can be readily represented to e.g. explore the implications of plantation establishment and/or clearing.</td>
<td>A separate set of carbon model parameters are associated with each land cover class, to allow between-vegetation type difference in vegetation growth, allometry, biomass etc. to be simulated.</td>
</tr>
<tr>
<td>Soil layer</td>
<td>Categorical</td>
<td>Rasterised composite of two soil data spatial databases (McKenzie et al. 2000; Western &amp; McKenzie 2006), with</td>
<td>Currently only soil water holding capacity is used in the modelling. Many other attributes are available for</td>
</tr>
</tbody>
</table>
approximately 40 soil attributes.

Slope

Continuous

Slope (degrees); calculated from the DEM.

Used in the fire algorithm to determine rate of spread within a gridcell.

Management layer(s)

Categorical

A layer defining the spatial extent and timing of prescribed management burns, timber harvesting, clearing, plantation establishment.

Used to define the management options.

**Temporal data**

Timeseries data requirements for DLS include selected SILO climate variables, and derived quantities (Table 3).

Table 3: Timeseries data required by DLS.

<table>
<thead>
<tr>
<th>Timeseries data</th>
<th>Description</th>
<th>How used</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILO daily climate data for each climate zone defined in the ‘Climate zones’ spatial layer.</td>
<td>Daily rainfall, maximum temperature, minimum temperature, relative humidity.</td>
<td>Daily quantities summed to monthly for the carbon and water balance calculations. Rainfall used to define the ‘P’ term in the water balance.</td>
</tr>
<tr>
<td>Wind speed; wind direction</td>
<td>Daily values generated at random using statistics from the nearest weather station (IDCJCM0037_071010 Kiandra; <a href="http://www.bom.gov.au/climate/data">http://www.bom.gov.au/climate/data</a>).</td>
<td>Used in the calculation of FFDI (see below), and in the spread behaviour of the fire once ignited.</td>
</tr>
<tr>
<td>Forest Fire Danger Index (FFDI)</td>
<td>Calculated according to Noble <em>et al.</em> (1980) using the drought factor (DF) calculation of Finkele <em>et al.</em> (2006). An index to indicate the current (daily) danger posed by unplanned wildfire. Required quantities to calculate the index include daily rainfall, relative humidity, and windspeed.</td>
<td>Used to determine the probability of wildfire ignition.</td>
</tr>
</tbody>
</table>
In addition to the spatial and temporal data listed above, a number of other datasets are also currently loaded into computer memory, and are available within the software for viewing, but are not currently used in any calculations. Some of these are simply to help visualise the landscape (e.g. 2002 satellite image & rendered hillshade image), whereas others are included in anticipation of further model development (e.g. topographic wetness index, aspect, and a range of currently unused soil and climatic attributes).

### 4.2.4 Submodel descriptions

#### Carbon submodel

The structure of the carbon submodel is shown in Figure 6. The underlying equations and parameters are described in Appendix A. The key features of the carbon submodel are:

- Living vegetation carbon is represented by four pools (leaf, stem, branch, root).
- Litter carbon is represented by four pools (leaf litter, standing dead coarse woody debris (CWD), grounded CWD, root litter).
- Soil organic carbon dynamics are described by the RothC model (Jenkinson 1990; Jenkinson & Coleman 1994), which comprises four pools involved in the cycling of terrestrial carbon (humus, decomposable and resistant plant material, and microbial carbon), and a single inert carbon pool (IOM).
- NPP is calculated as a two-stage process. First, light-limited NPP is calculated assuming other resources are not limiting. This is achieved through application of the simple light-use efficiency photosynthesis model of Roderick et al. (2001). Second, an estimate of ecosystem-level photosynthetic water use efficiency ($\text{H}_2\text{O}$ required to photosynthetically fix $\text{C}$) is used to calculate whether there is enough available soil water to support the light-limited NPP prediction (Budyko 1980). If not, then NPP is reduced on a pro-rata basis (Appendix A). This is a very simplistic approach to plant growth, and its limitations and potential for improvement are discussed in the final section.
- There is an explicit feedback between NPP and leaf biomass. This is because NPP is a function of fPAR, and fPAR is a function of total leaf area (which is here assumed related to total leaf mass). To prevent a runaway feedback between NPP and fPAR, resulting in either zero fPAR, or maximal light-limited fPAR, vegetation buffering is used to stabilise the relationship, whereby the proportion of NPP allocated to leaf biomass is negatively correlated with fPAR (Appendix A). The simulates the observation that younger, regenerating forests allocate proportionally more of their NPP to leaf production.
Figure 7  Diagrammatic representation of the DLS linking environmental disturbance with the carbon and water cycles. Blue represents water, green is carbon, and red for disturbance. The equations representing the stocks and fluxes of carbon and water are described in Appendix A. The equations are location specific, in that a separate ‘version’ of the model is run for each gridcell (depicted by the arrow pointing from a gridcell within the landscape), thus explicitly including topographic and climatic variability between gridcells.

Water submodel

The structure of the water submodel is also shown in Figure 6, and comparison with Figure 1 shows the overall structure remains unchanged from that described in the simple conceptual model. The underlying equations and parameters are described in Appendix A. The key features of the water submodel are:

- For every gridcell the water content of the soil is represented by a single mass; there is no segregation into different depth soil layers. Soil water holding capacity for each gridcell is read from the input soil layer.
- Irrigation is assumed to be zero, and the R and D terms are combined into a single runoff term.
- Total catchment runoff is the simple sum of the contributing runoff across all gridcells.
• Of the total evapotranspiration flux (E+T), T is calculated from an ecosystem water use efficiency parameter, set at 0.0014 Kg C fixed per Kg water transpired (Budyko 1977; Mohren 2002), and E is arbitrarily set at 20% of T.

This is clearly a very simplistic approach to modelling catchment hydrology, and was included merely as a ‘placeholder’ function. Despite its simplicity, it is capable of capturing the overall (cumulative) observed streamflow record, including the influence of significant rainfall events (see Section 4.3.1).

**Disturbance (fire) submodel**

For this initial implementation of the model the only disturbance that has been specified is fire.

Prescribed fire is simulated via a user-defined spatial layer that defines the extents and timings of the prescribed burning regime. The impacts of prescribed fire (Equations 5-7) are simplistically modelled as constant fractions, with default values of 40% of leaf litter and 40% of CWD litter consumed. These fractions can be altered via the model interface.

Modelling wildfire regimes within landscapes is a significant research challenge. Approaches range from simply defining *a priori* the area burnt and then applying the fire like a ‘cookie cutter’ (as per the prescribed burn), through to fire spread algorithms that take as their inputs weather conditions and fuel loads, and then through a series of rules and/or physical models, ignite, propagate and extinguish the fire across the landscape (Keane et al. 2004).

Although scientifically and computationally more demanding, this latter approach is adopted in DLSv0.1. This is because one of the primary aims of the analysis is to explore management impacts on wildfire occurrence; hence wildfire behaviour needs to evolve from the model equations, rather than be specified *a priori*. Also, for future development we wanted to leave open the possibility of exploring the potential impacts of climate change, of which a key concern are changes to landscape structure and function, and feedbacks with the climate system, including fire disturbance.

An initial ‘placeholder’ fire-spread algorithm was therefore implemented in order to provide an illustration of the general concept. Further development and/or substitution of this algorithm with alternative equations/models is required in order to more realistically simulate natural wildfire dynamics.

**Wildfire algorithm**

**Ignition**

The McArthur Forest Fire Danger Index (FFDI) is calculated on a daily basis from the input climate data (Table 3). Two parameters define wildfire ignition within the landscape. The first is a FFDI threshold over which wildfire can successfully propagate (default value set to 20); the second is a simple probability of ignition for days above that threshold (default value 0.1). I.e. if there is a day with a FFDI > 20, then the probability of a fire occurring is 0.1.
When a fire event is triggered, a location is selected at random within the spatial extent of the dataset, and that cell is ignited.

Spread

Wildfire spread is achieved via a process akin to a cellular-automata (Wolfram 1984), whereby when one a cell is burnt, it ignites neighbouring cells. The rules governing the rate and direction of spread are as follows:

1. The fire advances on an hourly timestep. In the current implementation weather only varies from day-to-day, therefore in practice the timestep is daily. However it is well know that sub-daily patterns of temperature, wind, fuel moisture etc. strongly influence fire behaviour. The hourly timestep was imposed in anticipation of future, more realistic, changes to the fire spread algorithm, including the generation of sub-daily weather variations (Cary & Gallant 1997).

2. Once ignited, a grid cell burns until it is fully consumed, at a rate of spread defined by Noble et al. (1980), which is a function of FFDI, current fuel load (i.e. the appropriate carbon stocks that are given by the carbon submodel), and average ground slope within the gridcell.

3. Similar to prescribed fire, the amount of fuel combusted is simplistically modelled as constant fractions, with default values of 75% of leaf litter, 75% of CWD litter consumed, and 5% each of leaf, stem and branch consumed. These fractions can be altered via the model interface.

4. Once fully consumed a gridcell then ignites its neighbours. Neighbours immediately adjacent are ignited based on wind direction and their relative topographic position (upslope vs. downslope). If wind speed is sufficiently strong (default value 20km/hr) then n non-adjacent gridcells up to a distance d down wind from the current gridcell are ignited to simulate spotting activity. The spotting distance d is also calculated using the formulae given by Noble et al. (1980), and is again included merely as a placeholder prior to inclusion of a more realistic function.

Extinguishment

Fire spread continues until the rate of spread within all currently burning gridcells falls below a threshold (default 5m/hr), or >2mm of rain falls. Active fire suppression is not included in this preliminary version of the model.

Figure 7 shows the typical development of a modelled fire according to the above algorithm. For the test landscape, and using historical climate data, the above parameter settings result in 1-2 large wildfires per 100 years (burning > 75% of the catchment), and 3-4 smaller fires (< 75% of the catchment). In broad terms this is similar to the occurrence of fire recorded historically for this region (Zylstra 2003).
Figure 8  Example of wildfire development across the test catchment over a 33hr period. The green represents unburnt areas, the black are areas that have been burnt, and the yellow is the active fire front. The final two panels show the Digital Elevation Model and terrain relief, respectively. The scale for the DEM is shown in Figure 4.
4.3 Model performance

Although the current equations and submodels underlining the DLS and their associated parameters have been neither tested nor validated, it is of interest to explore the ‘raw’ model behaviour, to confirm that the results are ecologically and physically sensible.

It is important to stress that the results shown below are at best hypothetical, and although the analyses are based on data specific to the Goobragandra test catchment, this does not guarantee the stocks and fluxes of carbon and water predicted by the model, and the emergent wildfire regime, in any way resembles reality.

The purpose of the model development is to demonstrate the linkages among the key submodels, and to illustrate how integrative landscape analyses can be conducted, and how the results can be analysed and interpreted. Further submodel development, combined with a rigorous program of observation-based calibration and validation, is required to transform this demonstration framework into a tool suitable for delivering practical management advice.

4.3.1 DLS prediction of carbon and water balance

Carbon stocks and fluxes

Figure 8 shows the time-course of changes in vegetation, litter and soil carbon over a 100 year simulation period, 1900 to 2000, in the absence of any wildfire. To provide the initial starting condition, a ‘spin-up’ of 3x100 year periods was run, and the carbon stocks at the end of that period used to initialise the runs shown in Figure 8. Although uncalibrated, the predicted stocks and fluxes are broadly consistent with our knowledge of other eucalypt-dominated forests. Above-ground carbon biomass is approximately 100tC/ha; ground litter is approximately 5tC/ha and Net Primary productivity 5-6 tC/ha/yr.

Water balance

The ecosystem water use parameter was set at 0.0014gC/gH₂O transpired. This resulted in an approximate agreement between observed and predicted cumulative catchment streamflow (Figure 9a), and is similar to values reported elsewhere for native forests (Budyko 1977 [0.0016]; Mohren 2002 [0.0015-0.0025]. Monthly relative soil water content fluctuates between periods where the soil is relatively well saturated, to periods where rainfall is less and the water content is drawn down (Figure 9b).

The spatial distribution of above-ground carbon and relative soil water content are shown in Figure 10.
Figure 9. Catchment-scale annual time series predictions by DLS for selected carbon outputs.

Above-ground vegetation carbon

Ground litter

Net Primary Productivity (NPP)
Figure 10. Aspects of the catchment water balance predicted by DLS (a) Observed vs. predicted cumulative streamflow. (b) Monthly relative soil water content.
Figure 11. Example spatial outputs from the DLS (simulation date May 1952) (a) Above-Ground vegetation carbon. (b) Relative soil water content. The low vegetation biomass and relative high soil water content of the pasture areas is clearly visible (see Figure 4b for land cover map).

(a)

(b)
4.4 Example management scenarios

To illustrate the intended analysis capacity of the software, two hypothetical scenarios were developed and the results presented in the form of the Landscape Management Assessment Charts described in Section 3. These scenarios involve assessing impacts of prescribed hazard reduction burning and plantation establishment on catchment hydrology, carbon storage, wildfire risk to infrastructure, and spatial habitat heterogeneity (a proxy biodiversity index).

Note these scenarios are entirely fictional, and because the model parameters have not been calibrated the results are similarly hypothetical. Choosing alternative (more realistic) parameter values would likely lead to significantly different outcomes.

4.4.1 Scenario 1. Efficacy of prescribed burning for protecting infrastructure, and implications for other ecosystem values.

This analysis follows the example used to illustrate the concept of the Landscape Management Assessment Chart in Figure 3, whereby a regime of prescribed burning is introduced to protect key infrastructure located within the landscape. Figure 11 shows the implementation of the analysis. Figure 11a is the current land use, with some hypothetical buildings added to the non-forested areas. Figure 11b shows the intended extent of the prescribed burning. The scenario involved running the model for 100 years (1900-2000) with a range of prescribed burning frequencies (no prescribed burn, 1, 2, 5, 10, 20 and 30 years) applied to that area.

Figure 12. Overview of the first scenario. (a) two buildings were added to the landscape (arrowed), and they were protected by a buffer (brown area in (b)) within which regular hazard reduction burning was prescribed, at a range of frequencies.
Figure 13. Example LMAC for the scenario depicted in Figure 11, investigating the impacts of initiating a prescribed burning regime to protect key infrastructure within the landscape. Values represent the mean of each management option (PB frequency) over 1000 replicate simulations. For an indication of between-replicate variability see the second scenario.
The resulting LMAC suggests prescribed burning every 10 years or less reduces the probability of the infrastructure experiencing a wildfire in any given year from approximately 0.015 (i.e. once every 66 years) to 0.011 (once every 90 years). Prescribed burning at these frequencies also reduced the total area burnt by wildfire in the landscape by approximately 5%, and did not markedly affect either landscape carbon stocks nor catchment water flows, though with annual burning there was some indication of an increase in streamflow.

Whilst indicative of actual likely responses, the above results are sensitive to the assumptions built into the current version of the model surrounding the relationship between the fuel components removed by prescribed and wildfire respectively, and the fire behaviour model for which fuel load is a primary input.

**4.4.2 Scenario 2. Impact of plantation establishment on catchment flows, and implications for other ecosystem values.**

The second scenario addresses the question of what impact plantation establishment has on catchment water yields and carbon sequestration, together with ancillary impacts on wildfire risk. This analysis includes only two management options: (a) an ‘historical’ option that simulates the actual timecourse of plantation establishment in the catchment (Marcar et al. 2010), assuming an initial starting point of previous cleared pasture, and (b) a scenario that assumes no plantations were established (Figure 13). Because trees use more water than pasture, with plantation establishment catchment water yield is expected to decline, and total carbon stocks to increase.

Figure 14. Overview of the second scenario. (a) the multi-coloured areas within the plantation area indicate differing dates of plantation establishment (the majority of areas were planted since 1960). In the first management scenario the plantation patches were established according to these timings, and in the second management scenario (b) no plantation establishment was assumed, and the landscape comprised only pasture (brown) and native forest (blue) throughout the whole simulation period (1960-2000).
Figure 15. LMAC for the second scenario investigating the impacts of plantation establishment. Figures show mean and standard deviation of simulation results across $n=1000$ replicate runs.
For the second scenario a slightly different display format for the LMAC is adopted, illustrating the ability to show (as bar charts) different qualitative management options, in contrast to the continuous variation in prescribed burn frequency depicted in the first scenario. Scenario 2 suggests the impact of the historical plantation establishment, as compared to retaining the planted lands as pasture, led to an increase in landscape carbon storage over the period 1960-2000 of approximately 100,000 tC in living biomass (approximately 1.5% of total catchment biomass C), with a corresponding decline in catchment water yield of approximately 11 GL/yr. With a mean annual streamflow of 180GL/yr, this corresponds to a reduction in annual streamflow of approximately 6%. Predicted impacts on other ecosystem attributes were negligible.

For this scenario the index of habitat heterogeneity was defined as the spatial variability of above-ground living C (calculated as the spatial coefficient of variation). I.e. a landscape with patches of vegetation at different stages of the successional cycle is assumed to be more diverse than a landscape that is single-aged. Many other indices of biodiversity habitat are possible, including the use of spatial statistics to more comprehensively quantify the degree of patchiness, fragmentation etc. The simple between-gridcell statistic calculated here was used as a placeholder for a more complete set of habitat-related definitions, and to highlight how biodiversity attributes can be built into the framework.

Although these two scenarios are simplistic, and in many ways are unrealistic, they do show the potential for the development of more complex and realistic combinations of potential management actions, e.g. multiple activities asynchronous in both space and time. Such composite scenarios might include prescribed burning in different parts of the landscape and with different timings/frequencies, combined with timber harvesting in other areas, and/or plantation established elsewhere, etc.

5. KNOWLEDGE GAPS AND PRIORITIES FOR FURTHER DEVELOPMENT

The primary aim of this scoping study was to outline the design and implementation of a ‘proof of concept’ decision support software tool to facilitate spatially-explicit landscape analyses that consider simultaneously a number of different ecosystem attributes, with a focus on management impacts on carbon, water, fire regimes and biodiversity habitat.

The process of developing the conceptual framework (Section 2) and then translating that into a formal mathematical structure (Section 4) provided many insights into our current state of knowledge of landscape processes, and the many uncertainties faced when attempting to combine models of vegetation growth and decay, soil carbon dynamics, catchment hydrology and disturbance events in spatially complex terrain.

The submodels implemented in the software that describe the dynamics of carbon, water and disturbance were chosen to provide the simplest possible descriptions of the key underlying processes, thus facilitating full system coupling, though without explicitly including many important processes and patterns. This was done purposefully, recognising that it is always easier to incrementally add complexity onto an initially simple framework.
This final section reviews the major areas of development required to extend the current ‘proof of concept’ product into an operational tool. It also considers more broadly the data requirements for improving the rigor of model calibration and validation, and discusses opportunities for extending the scope beyond biophysical processes to include the socio-economic dimension.

5.1 Carbon

5.1.1 Plant growth / NPP

The process of fixing atmospheric carbon (Net Primary Productivity) is currently described using an extension of the light-use efficiency model of Roderick et al. (2001). In our formulation the primary limiters of growth are incoming solar radiation and water availability. Temperature does not directly affect plant photosynthesis, nor does atmospheric CO$_2$ concentration. Further development of the plant growth algorithm to include these additional factors would provide opportunities to extend the scope of the framework to explore climate change impacts on vegetation, water and disturbance regimes.

*Model development opportunities*

- The addition of CO$_2$ and temperature modifiers of growth and decomposition to facilitate global change studies.

5.1.2 Carbon allocation

The dynamic allocation of fixed photosynthate into plant organs is treated simplistically as constant allocation fractions, modified to proportionally allocate relatively more photosynthate to leaf production during the earlier stages of stand development (see Appendix A). This is consistent with other schemes proposed for allocation in terrestrial carbon models. In reality allocation of photosynthate is dynamic and varies both temporally and spatially.

*Model development opportunities*

- Optimality theory has been proposed as a paradigm for dynamically allocating photosynthate in plants (e.g. Schymanski et al. 2007). There may be opportunities to develop some of these ideas within DLS.

*Key knowledge gaps*

- How the allocation patterns of photosynthate to different plant tissues change through time.
- How the allocation patterns of photosynthate to different plant tissues change across space.
5.1.3 **Nutrients**

Vegetation requires the continuous supply of three basic factors: sunlight, water and mineral nutrients. The current framework does not explicitly account for variations in nutrient availability, particularly nitrogen and phosphorus, nor for disturbance impacts to the supply of these nutrients. Rather, nutrient constraints are embedded (or hidden) with the existing model parameter calibration. Nutrient constraints and feedbacks on carbon gain and vegetation water use is an important driver of vegetation dynamics, and improving the representation of these processes needs to be addressed during the next phase of development.

*Model development opportunities*

- Addition of linked nutrient (nitrogen and phosphorus) cycles to the carbon cycle.

*Key knowledge gaps*

- Quantifying the spatial and temporal availability and variability in nutrients within the soil and plant tissues, for model parameterisation and calibration.
- Quantifying the nature of the feedback between mineral nutrient availability and plant growth (NPP).
- How disturbance, particularly fire, interacts with the nitrogen and phosphorus cycles.

5.1.4 **Spatial environmental variability on stocks and fluxes**

At present the major spatial environmental variation considered by the carbon submodel comprises topographically-corrected solar monthly radiation, soil properties, some coarse within-catchment climatic variation, and an imposed map of vegetation distribution (tree, grass, plantation etc.). However many aspects of the C cycle are also sensitive to these variations, particularly the decomposition rate of litter, which is known to vary with temperature and moisture across topographic gradients.

*Model development opportunities*

- Making organic matter decomposition a function of within-landscape variability, particularly topographic variation in temperature and moisture regimes.

*Key knowledge gaps*

- Spatial and temporal changes in the rates of organic matter decomposition across landscape gradients.
- Spatial variability in living and litter and soil carbon stocks in native forests, particularly along environmental gradients.
- The RothC soil model is widely used in Australia and elsewhere, however its performance for simulating Australian native forest soils is yet to be determined.
5.2 Water

The current water model is rudimentary. It comprises a single bucket, with no influence of relative topographic position. Alternative schemes appropriate for landscape-scale runoff studies need to be reviewed. One alternative, similar to the existing ‘top-down’ approach currently in place, is that of Zhang et al. (2008), which provides additional soil water storage compartments, and opportunities for calibration to study catchments.

The current link between the carbon cycle and the transpiration flux of the water cycle is via a vegetation-specific constant ecosystem water use efficiency parameter. This parameter, like most others, will also vary both through time and across space.

Model development opportunities

- Extending the simple water model to include more than one soil compartment, and to properly account for the evaporation (E) and drainage (D) terms.
- Allowing the ecosystem water use efficiency parameter to be spatially and temporally variable.

Key knowledge gaps

- Representative ecosystem water use efficiency parameters for Australian vegetation.

5.3 Fire

The existing cellular-automata fire spread algorithm captures the major inputs and dynamics of fire behaviour, and was created primarily as a placeholder function. It has never been tested or validated against field data. There is however the possibility of replacing this function with pre-existing firespread algorithms that have been tested in Australian conditions, e.g. FireScape (Cary 2002).

There are many additional aspects of the fire algorithm that require careful attention, over and above the specification of fire ignition, propagation and extinguishment. These include the amounts of carbon in the different ecosystem pools (living, litter, soil) that are consumed in both prescribed fire and wildfire, and the efficiency with which they are consumed; the fate of carbon that is not consumed (e.g. transfers of living carbon to standing dead carbon CWD, transfers to soil IOM); and issues surrounding the representation of on-ground fire management, e.g. suppression.

Model development opportunities

- A review of existing fire spread models and/or opportunities for the further development of the existing algorithm needs to be made (see e.g. Keane et al. 2004).
Key knowledge gaps

- Validating model-predicted fire regimes at decadal-century timescales is difficult due to (a) limitations of the observational record and (b) the relative long period between major bushfire events in temperate forest systems.
- Fuel consumption rates under different burning conditions and across environmental gradients.

5.4 Model calibration and testing

Parameter values for the implementation described in Section 4 were selected either based on previous analyses, or by simple manual tuning. However, automation of model calibration via a search algorithm, and using multiple observational data to constrain parameter estimates, provides a more robust solution. A number of methods are available for conducting such ‘model-data fusion’ calibration (Trudinger et al. 2007). These can either be embedded as part of the model code and analysis (Roxburgh et al. 2006), or can be run externally to the model (e.g. the PEST software; http://www.parameter-estimation.com/html/pest_overview.html).

Parameter estimation is a critical component of any model development, and opportunities and limitations for implementing a formal parameter optimisation procedure in DLS need to be explored. This involves not only selecting an appropriate algorithm, but also assessing the availability of field data on which to base the optimisation, and assessing constraints associated with the computational demands required to undertake such calculations.

5.5 Other opportunities

5.5.1 Biogeochemistry vs. ecology

In the current implementation vegetation carbon is modelled via the biogeochemistry of the carbon cycle, i.e. the state variable has units tC/ha – in effect vegetation is represented as a ‘green slime’. However it is well known that ecological aspects of the system are important controllers of the distribution of carbon across landscapes (e.g. variation in species distribution patterns) and interactions with the fire regimes (e.g. re-seeders vs. re-sprouters). Such ecological details are simulated in biochemical models through changing the allocation coefficients, growth rates etc. of the component vegetation. The carbon stock equations can also be separated into canopy and sub-canopy vegetation, providing the capacity to separate trees and shrubs/herbs, and overstorey fuels from understorey fuels. In terms of further developing the fire behaviour submodel this is likely to be a valuable modification

However, there may be arguments that a more ecological/population-based approach to modelling carbon dynamics is warranted (e.g. Dean et al. 2003, 2004). This deserves some consideration.
5.5.2 The socio-economic dimension

As a starting point the current framework has focussed on the biophysical aspects of landscape function. However many of the events that take place in landscapes, and all of the decisions that are made, are done within the context of both economics and societal constraints. An obvious extension of the current scope of the framework is the inclusion of both economic constraints and the impacts of human decision making on defining the scenarios to be tested.

5.5.3 Landscape Management Assessment Charts

There are many additional ecosystem response variables that could be included within the LMAC framework, over and above the indices shown in Figures 13 & 14. For example total wildfire GHG emissions, carbon sequestration rates, and various measure of vegetation heterogeneity that could be used for summarising biodiversity habitat. The range of variables of interest will be to some extent a function of the aims of any particular study, and can be added to the software as required.

5.5.4 Software development framework

A final question regards the best vehicle for developing and distributing such a system. The ‘proof of concept’ software was coded in a stand-alone compiled language (Borland Delphi), but this was done mostly for convenience; programs written and compiled in dedicated programming languages like Delphi or C run much faster than interpretative systems such as R or VBA; programs and data are stand-alone and require no additional software requirements to run; and finally many of the algorithms for numerical analysis, data manipulation, visualisation, and for parallelising the code (to take advantage of modern multi-core processors) were pre-existing, facilitating relative rapid development of the DLS.

Despite these advantages, alternative options including linking the modelling framework to existing software, e.g. ArcGIS, or even in a form suitable for a web interface. This requires further consideration.

5.6 Further development summary

Short-term priorities to advance the tool from ‘proof-of-concept’ to a system capable of analysing a real case study are:

- Calibration / testing against multiple field data.
- Revision of the fire algorithm and associated parameter settings and assumptions.
- Revision of the simple single-bucket water model.
- Incorporation of nutrient constraints and feedbacks.

Intermediate-term priorities to increase the scope and utility of the tool:

- Extension of the carbon model to provide opportunities for assessing climate change impacts.
• More explicit linking between carbon fuel pool categories and the fire behaviour algorithm.
• Addition/incorporation of socio-economic algorithms/constraints.

6. REFERENCES


APPENDIX A. DYNAMIC LANDSCAPE SIMULATOR (DLS) V0.1
CORE MODEL EQUATIONS

The following equations describe the dynamics of carbon and water within a single gridcell of the landscape, and operate at a monthly timestep. The fire spread algorithm, described in the main text, is spatially contagious and runs at an hourly timestep.

**NPP**

Net primary production involves a two-stage calculation. The first stage calculates light-limited NPP using the light-use efficiency model of Roderick et al. (2001), that empirically accounts for the influence of the diffuse fraction of solar radiation

\[ NPP_l = e \frac{R_s}{R_0} \times f\text{PAR} \times R_0 \times 0.45 \]

Here \( e \) is the light use efficiency parameter (mol CO\(_2\) / mol PAR), \( R_s \) is global solar irradiance at the top of the canopy (provided to DLS as a monthly varying topographically corrected input data grid), \( R_0 \) is irradiance at the top of the atmosphere (calculated within DLS using standard trigonomic functions and the solar constant), \( f\text{PAR} \) is the fraction of incoming photosynthetically active radiation used for photosynthesis, and 0.45 accounts for autotrophic respiration.

\( e \) is calculated as

\[ e = 0.024 \frac{R_d}{R_s} + 0.012, \text{ where } \frac{R_d}{R_s} = 1.11 - 1.31 \frac{R_s}{R_0}, \text{ and is the diffuse fraction.} \]

\( f\text{PAR} \) is calculated from the current state of the vegetation as a step function, where:

\[ f\text{PAR} = \begin{cases} 0.95 & L \geq L_m \\ \frac{0.95}{L_m} \times L & L < L_m \end{cases} \]

Where \( L \) is the current leaf mass, and \( L_m \) is a user-defined parameter specifying the canopy leaf mass at which \( f\text{PAR} = 0.95 \).

\( NPP_l \) does not include limitations due to other resources, e.g. water or nutrients. The second stage of the NPP calculation therefore adjusts this ‘potential’ NPP based on the availability of soil water, as determined by the soil model (see below).

Using the water use efficiency parameter for each vegetation type (WUE, t\( C \) fixed / t water transpired), the amount of soil water required to fix the predicted potential \( NPP_l \) is calculated as:

\[ W_R = NPP_l \times \frac{1}{WUE} \]
Where $NPP_l$ is in units tC/ha, and therefore $W_R$, the mass of water required to support that amount of growth, and is also in t/ha.

This quantity is compared against the available soil water content for the current month (tC/ha)

$$W_A = (SWC + P) \times 0.9$$

Where $W_A$ is the soil water available for growth, and $P$ is precipitation for the month. The 0.9 is an assumption that the last 10% of water in the soil is unavailable to plants. One of the limitations of the current monthly soil water model becomes apparent here, where water availability is calculated at the start of the month, and therefore does not include any information on the timing of rainfall during the month. I.e. it assumes all rain falling is available for growth. This is clearly unrealistic, but can be remedied through modelling water use at a finer timescale, e.g. daily.

If $W_A \geq W_R$ then all light-limited predicted growth $NPP_l$ takes place over the month, i.e.

$$NPP = NPP_l$$

and the transpiration flux $T = W_R$.

If $W_A < W_R$ then the amount of growth is apportioned linearly, reflecting water limitation:

$$NPP = W_A \times WUE$$

and the transpiration flux $T = W_A$.

**Allocation**

In the absence of any buffering growth response of the vegetation the above scheme for calculating $fPAR$ leads to a situation with either maximum $fPAR = 0.95$, or minimum $fPAR = 0.0$ and no biomass, depending on current allocation. This is due to the feedback loop:

less leaf mass $\rightarrow$ lower $fPAR$ $\rightarrow$ lower NPP $\rightarrow$ less leaf mass $\rightarrow$ lower $fPAR$ …

In **DLS** the feedback loop is stabilised through making the relative allocation of photosynthate to leaf mass ($a_{leaf}$) a negative function of $fPAR$:

$$a_{leaf}' = (a_{leaf}_{regen} - a_{leaf}) \times e^{-8\times fPAR} + a_{leaf}$$

Where $a_{leaf}'$ is the current (dynamic) allocation of photosynthate to leaf, $a_{leaf}$ is the allocation in a mature stand (default value 0.3 for native forest), and $a_{leaf}_{regen}$ is the allocation in a young regenerating stand (default value 0.8 for a native forest). For these parameters the relationship looks like this:
This function simulates the observed change in allocation in developing forest stands, with a bias towards leaf production during early growth.

The allocations to branch, stem and root are adjusted to ensure the sum of the allocations is always unity.

**Water**
The current water model is very simplistic, and is included as a placeholder until a more rigorous formulation is developed.

The soil water holding capacity ($WHC$) is input via the spatial soil map data. It is usually given in mm, but within the software this (and other) water quantities are converted to mass units (t/ha), based on the current gridcell area of the simulation, and assuming density of water $= 0.9982071\ (20^\circ C)$.

Precipitation ($P$) is provided as input data.

The transpiration flux, $T$, is defined above, and is a function of current plant growth.

Drainage ($D$) is set to 0.0 (!).

Irrigation is set to 0.0.

Evaporation ($E$) is set at a constant proportion of $T$ (!). Default value 0.2.

The change in soil water content ($SWC$) over the month is given by

$$SWC_{\text{end}} = SWC_{\text{start}} + P - E - T$$

If $SWC$ at the end of the month ($SWC_{\text{end}}$) exceeds $WHC$ then the excess is used to calculate runoff ($R$):

$$R = \begin{cases} 
0 & \text{if } SWC_{\text{end}} \leq WHC \\
SWC_{\text{end}} - WHC & \text{if } SWC_{\text{end}} > WHC
\end{cases}$$

$$SWC = \begin{cases} 
WHC & \text{if } SWC_{\text{end}} > WHC \\
SWC_{\text{end}} & \text{if } SWC_{\text{end}} \leq WHC
\end{cases}$$

Relative soil water content ($rSWC$) is given by

$$rSWC = SWC / WHC$$
Carbon stocks & fluxes

Living carbon

\[
\frac{dC_{\text{Leaf}}}{dt} = \alpha_{\text{Leaf}} \times \text{NPP} - \frac{C_{\text{Leaf}}}{L_{\text{Leaf}}}
\]

\[
\frac{dC_{\text{Stem}}}{dt} = \alpha_{\text{Stem}} \times \text{NPP} - \left(1 - p_{\text{LIVING}_\text{CWDS}}\right) \frac{C_{\text{Stem}}}{L_{\text{Stem}}} - p_{\text{LIVING}_\text{CWDS}} \frac{C_{\text{Stem}}}{L_{\text{Stem}}}
\]

\[
\frac{dC_{\text{Branch}}}{dt} = \alpha_{\text{Branch}} \times \text{NPP} - \left(1 - p_{\text{LIVING}_\text{CWDS}}\right) \frac{C_{\text{Branch}}}{L_{\text{Branch}}} - p_{\text{LIVING}_\text{CWDS}} \frac{C_{\text{Branch}}}{L_{\text{Branch}}}
\]

\[
\frac{dC_{\text{Root}}}{dt} = \alpha_{\text{Root}} \times \text{NPP} - \frac{C_{\text{Root}}}{L_{\text{Root}}}
\]

Litter / CWD carbon

\[
\frac{dC_{\text{LeafLit}}}{dt} = \frac{C_{\text{Leaf}}}{L_{\text{Leaf}}} - h_{\text{LeafLit}} \left(1 - h_{\text{LeafLit}}\right) \frac{C_{\text{LeafLit}}}{L_{\text{LeafLit}}}
\]

\[
\frac{dC_{\text{CWDS}}}{dt} = p_{\text{LIVING}_\text{CWDS}} \frac{C_{\text{Stem}}}{L_{\text{Stem}}} + p_{\text{LIVING}_\text{CWDS}} \frac{C_{\text{Branch}}}{L_{\text{Branch}}} - p_{\text{CWDS}_\text{CWDS}} \frac{C_{\text{CWDS}}}{L_{\text{CWDS}}} - \left(1 - p_{\text{CWDS}_\text{CWDS}}\right) \frac{C_{\text{CWDS}}}{L_{\text{CWDS}}}
\]

\[
\frac{dC_{\text{CWDG}}}{dt} = \left(1 - p_{\text{LIVING}_\text{CWDS}}\right) \frac{C_{\text{Stem}}}{L_{\text{Stem}}} + \left(1 - p_{\text{LIVING}_\text{CWDS}}\right) \frac{C_{\text{Branch}}}{L_{\text{Branch}}} + p_{\text{CWDS}_\text{CWDS}} \frac{C_{\text{CWDS}}}{L_{\text{CWDS}}} - h_{\text{CWDG}} \frac{C_{\text{CWDG}}}{L_{\text{CWDG}}}
\]

\[
\frac{dC_{\text{RootLit}}}{dt} = \frac{C_{\text{Root}}}{L_{\text{Root}}} - h_{\text{RootLit}} \left(1 - h_{\text{RootLit}}\right) \frac{C_{\text{RootLit}}}{L_{\text{RootLit}}}
\]

Soil organic carbon (SOC)

Dynamics are defined by the RothC model (ref). There are 5 SOC pools with decomposition a function of moisture status, temperature and soil clay content. The five pools are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial biomass (MIC), Humus (HUM) and an inert pool (IOM)

Ancillary fluxes

i) Rate of conversion of litter to SOC; provided as input to RothC

\[
h_{\text{LeafLit}} \frac{C_{\text{LeafLit}}}{L_{\text{LeafLit}}} + h_{\text{RootLit}} \frac{C_{\text{RootLit}}}{L_{\text{RootLit}}} + h_{\text{CWDG}} \frac{C_{\text{CWDG}}}{L_{\text{CWDG}}}
\]
ii) Total litterfall to ground

\[ \frac{C_{\text{Leaf}}}{L_{\text{Leaf}}} + (1 - p_{\text{LIVING}_{-}\text{CWDS}}) \frac{C_{\text{Stem}}}{L_{\text{Stem}}} + (1 - p_{\text{LIVING}_{-}\text{CWDS}}) \frac{C_{\text{Branch}}}{L_{\text{Branch}}} \]

iii) Heterotrophic respiration

\[ (1 - h_{\text{LeafLit}}) \frac{C_{\text{LeafLit}}}{L_{\text{LeafLit}}} + (1 - p_{\text{CWDS}_{-}\text{CWDS}}) \frac{C_{\text{CWDS}}}{L_{\text{CWDS}}} + (1 - h_{\text{CWDS}}) \frac{C_{\text{CWDS}}}{L_{\text{CWDS}}} + (1 - h_{\text{RootLit}}) \frac{C_{\text{RootLit}}}{L_{\text{RootLit}}} \]

Symbol definitions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPP</td>
<td>Net Primary Production (tC/ha/yr)</td>
</tr>
<tr>
<td>(C_{\text{Leaf}}, C_{\text{Stem}}, C_{\text{Branch}}, C_{\text{Root}})</td>
<td>Carbon stocks in living vegetation components</td>
</tr>
<tr>
<td>(a_{\text{Leaf}}, a_{\text{Stem}}, a_{\text{Root}}, a_{\text{Branch}})</td>
<td>Allocation fractions of photosynthate ((NPP)) to plant organs. Must sum to 1.0.</td>
</tr>
<tr>
<td>(C_{\text{LeafLit}}, C_{\text{RootLit}})</td>
<td>Dead leaf and root litter</td>
</tr>
<tr>
<td>(C_{\text{CWDS}}, C_{\text{CWDS}})</td>
<td>Fallen coarse woody debris on the ground, and dead standing stags</td>
</tr>
<tr>
<td>(L_{\text{Leaf}}, L_{\text{Stem}}, L_{\text{Branch}}, L_{\text{Root}}, L_{\text{LeafLit}}, L_{\text{RootLit}}, L_{\text{CWDS}}, L_{\text{CWDS}})</td>
<td>Residency times of carbon in the various pools (=1/turnover time)</td>
</tr>
<tr>
<td>(p_{\text{LIVING}_{-}\text{CWDS}})</td>
<td>Proportion of living branch and stem carbon that is transferred to the standing CWD pool</td>
</tr>
<tr>
<td>(1 - p_{\text{LIVING}_{-}\text{CWDS}})</td>
<td>Proportion of living branch and stem carbon that is transferred to the ground CWD pool</td>
</tr>
<tr>
<td>(p_{\text{CWDS}_{-}\text{CWDS}})</td>
<td>Proportion of standing dead CWD that is transferred to the ground CWD pool</td>
</tr>
<tr>
<td>(1 - p_{\text{CWDS}_{-}\text{CWDS}})</td>
<td>Proportion of standing dead CWD that is decomposed</td>
</tr>
<tr>
<td>(h_{\text{CWDS}}, h_{\text{RootLit}}, h_{\text{LeafLit}})</td>
<td>Humification fractions specifying the proportion of litter entering the SOC pool</td>
</tr>
</tbody>
</table>
APPENDIX B. SOFTWARE INTERFACE

A screen image of the software after loading a project is shown below. The main form currently comprises three menu items and six tabbed pages.

The first tabbed page (shown above) displays the input data. The above map shows the DEM, and the timeseries is monthly rainfall. Tabs 2-4 are where the parameter values for the carbon, water and fire sub-models are stored. Tab 5 is shown below and displays various outputs as the model runs through time. These include timeseries charts of a number of outputs, barcharts of landscape-scale summaries of various quantities, and the choice of two different spatial output maps.
The ‘Model run’ tab is also where the scenario is set up and controlled. E.g. the timeframe over which the analysis runs (1900-2001 above), where the numerical integration method is selected, and also hidden under the ‘Simulation builder’ tab are the settings for the number of management scenarios being considered, and the number of replicate runs of each scenario to be run. The final tab (‘Simulation results’) displays the Monte-Carlo results in the form of a Landscape Management Assessment charts (shown below).

Menu items

The first menu item provide standard project file input/output functionality:

- New project
- Open existing project...
- Reopen
- Clear recently used list
- Save project
- Save project As...
- Exit

The second menu list some special run modes, including looping the climate data for ‘top-and-tailing’ the input timeseries; for saving the results at the end of a run to be used as initial conditions for the next run, and loading in the spatial data at a reduced resolution. This is used
principally for debugging (to allow the whole landscape to be rapidly run). This also provides opportunities for exploring the sensitivity of model results to the spatial grain, and therefore for optimising the spatial grain for any given analysis.

The final menu item provides options for controlling the behaviour of the parallel processing capabilities, for computers with greater than one CPU (see Appendix C).

APPENDIX C. TECHNICAL NOTES

Numerical integration

Two ODE (ordinary differential equation) solver algorithms are provided. (a) Euler’s method with a constant step size provided via the model interface, and (b) the 4th order Runge-Kutta adaptive stepsize algorithm (Press et al. 1986). Although the Runge-Kutta method provides the best accuracy, it is computationally significantly slower. For the simulations reported above Euler’s method with a stepsize of 2 was used (i.e. integrating from time \(a\) to time \(b\) involved a single intermediate calculation). A stepsize of 2 was found to produce results numerically very similar to Runge-Kutta.

Parallel processing

Modern personal computers often have two or more processors. Traditional programming languages like Delphi operate sequentially, and hence cannot natively take advantage of the potential power of conducting calculation in parallel. In the DLS the freely available ‘JIBU’ programming library was imported into Delphi to facilitate parallel coding (http://www.axon7.com/flx/documentation/jibu_for_delphi). For the quad-core PC used to develop the software, this resulted in up to a 3.7x increase in processing speed compared with compiling the program to run in traditional sequential mode.
For more extensive simulations (either temporally or spatially) use of the CSIRO Citrix/Server cluster is being investigated. This infrastructure is currently being developed by CSIRO IM&T, and provides access to significant parallel-processing capacity, extending many-fold the analysis capacity available on a single desk-top PC.

**Random number generation**

Monte-Carlo computations require a reliable random number generator. Alas, many random number generators produce less than ideal results. In the *DLS* the algorithm Ran3 of Press et al. (1986) is used to generate all random deviates.
CSIRO and the Flagships program

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills. CSIRO initiated the National Research Flagships to address Australia’s major research challenges and opportunities. They apply large scale, long term, multidisciplinary science and aim for widespread adoption of solutions.